



Primary reserve studies for high wind power penetrated systems

Das, Kaushik; Altin, Müfit; Hansen, Anca Daniela; Sørensen, Poul Ejnar; Abildgaard, Hans

Published in:
Proceedings of 2015 IEEE PowerTech

Link to article, DOI:
[10.1109/PTC.2015.7232764](https://doi.org/10.1109/PTC.2015.7232764)

Publication date:
2015

Document Version
Peer reviewed version

[Link back to DTU Orbit](#)

Citation (APA):
Das, K., Altin, M., Hansen, A. D., Sørensen, P. E., & Abildgaard, H. (2015). Primary reserve studies for high wind power penetrated systems. In *Proceedings of 2015 IEEE PowerTech IEEE*.
<https://doi.org/10.1109/PTC.2015.7232764>

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Primary Reserve Studies for High Wind Power Penetrated Systems

Kaushik Das*, Müfit Altin,
Anca D. Hansen, Poul E. Sørensen
Department of Wind Energy
Technical University of Denmark
Risø, Denmark
*kdas@dtu.dk

Hans Abildgaard
Power System Planning
Energinet.dk
Fredericia, Denmark

Abstract—With high penetration of non-synchronous wind generations replacing conventional generators, the inertia of power system will reduce. A large disturbance in such a power system can cause faster frequency change in this power system and might invoke emergency defence strategies like underfrequency load shedding. The impact of low inertia caused due to displacement of conventional generators by wind penetration on the power system frequency is investigated in this paper. The possibilities of improving frequency with increase in primary reserve supplied from conventional generators are analyzed. This paper further explores the capabilities of wind turbines to provide support during underfrequency to prevent load shedding. Maximum wind penetration possible without causing load shedding following a large disturbance is also investigated.

Index Terms—Low inertia, primary reserve, underfrequency load shedding, wind generation

I. INTRODUCTION

Wind energy will increasingly make large contributions to electricity market throughout the world. It is expected that wind energy in 2020 will meet 15.7% of European electricity demand from 230 GW, and by 2030, 28.5% from 400 GW [1]. These new generations will replace the conventional generators (mainly during high wind scenarios). The large controllable, variable speed wind generators are connected to the system through power electronic converters. Therefore the rotational mass of wind turbine is physically isolated from the network, as a result, the wind generators do not contribute to the inertia of the system. Consequently, higher the penetration of wind generations replacing conventional generations, lower is the inertia of the system. A system with lower inertia experiences higher frequency fluctuations following a large disturbance like disconnection of a generator. This effect is more prominent in islanded power systems. Fast decline of frequency following a large disturbance can cause short term frequency instability [2]. Different types of frequency control processes, viz. primary, secondary and tertiary control are employed to restrict the frequency decline and stabilize the frequency.

In order to limit the frequency from going too low and exceeding the acceptable limits (for example - 49 Hz in Europe), primary control is employed. Primary control is activated within 20-30 s after the disturbance and utilizes reserved power from dedicated generators referred as primary reserves. After the frequency is contained by primary control, secondary control is activated to restore frequency to its nominal steady state value and replenish the used primary reserves. Secondary control is generally performed by Automatic Generation Control (AGC) using reserves called secondary reserves. Secondary control is activated within 30s - 15 min after the disturbance. Tertiary control is generally manual and slow. Primary function of tertiary control is to free the activated secondary reserves. However, following a large disturbance, if all of the reserves are exhausted and are not fast enough to contain the frequency, the system may enter in an emergency state. Special defence strategies called special protection systems (SPS) are required to defend against instabilities in emergency state and prevent blackout. Underfrequency load shedding (UFLS) is one such SPS to prevent frequency instability [3]. UFLS is only considered as last resort since it causes economic losses and discomfort to consumers. Therefore, all the available resources to prevent underfrequency should be employed before UFLS. Generally, UFLS starts at 49 Hz as per ENTSO-E recommendation [4].

The work presented in this paper is concerned mainly with primary control. Primary control is traditionally provided by conventional generators equipped with governors. If the inertia of the system is low, the frequency decline following a large disturbance in the system can be very fast. In this case, traditional primary control can be too slow to contain the frequency decline. Wind turbines are capable of providing frequency support in this situation since power electronics based power control in wind turbines are very fast. Frequency support from wind turbines can be of two types - inertial control and droop control or primary control. Inertial control from wind turbines can increase the active power outputs utilising the stored energy in the rotating masses of wind turbines for very short time. Wind turbines can only provide droop control support when they are operating with reserves [5], [6]. This means that they have to be operated in derated

The research leading to these results has received funding from the European Union Seventh Framework Programme under grant agreement n°283012

condition and producing much lesser output power than input available wind power, which is an expensive option.

This paper analyses the effect of decreasing system inertia by displacement of conventional generators with wind turbines on frequency decline following a major disturbance in the system. This paper further studies whether this frequency declination can be mitigated with the help of primary control through primary reserves supplied from conventional generators. The success of the control is measured by its ability to prevent the frequency decline from triggering UFLS. The primary reserves are expected to be completely deployed within 30s after the disturbance and the secondary reserves start acting after 30s. Therefore, it is investigated that whether minimum frequency (frequency nadir) can be limited within 49 Hz within 30s after the disturbance. Maximum amount of wind penetration that can be done without triggering UFLS is explored through different case studies. Comparative studies between a case when primary reserves are supplied from conventional generators and a second case where primary reserves are supplied from wind turbines are carried out.

The structure of the paper is as following: modelling of a power system with large wind power penetration is described in section II. Section III describes the results of the case studies performed in the system. Section IV concludes the paper while providing motivations for further research.

II. POWER SYSTEM MODEL

In the present investigation a power system model extracted from PEGASE system model [7] is used. PEGASE system is a synthetic model to represent the Pan-European network. The dynamic model of PEGASE has 16578 buses and 14044. The Western Denmark area equivalent power system from this synthetic model is used for the investigation. In order to observe the effect of low inertia in an island system, the interconnections with neighbouring areas are not considered. The following types of generations are considered in the analysis:

- Steam generator with classical governor.
- Hydroelectric generator.
- Gas turbine and combined cycle plant with single shaft turbine.
- Wind turbine modelled using IEC Generic Dynamic Model of wind turbines [8].

Loads are modelled as dynamic frequency dependent load with self-regulation capability of 1%/Hz [9]. UFLS settings are considered based on ENTSO-E recommendations. The first step of UFLS is 10% of the total loads at 49 Hz. Therefore, success criterion for the investigation is defined as the control of frequency nadir should be limited to 49 Hz.

Steam generator with classical governor used for the analysis as shown in Fig. 1 is from EUROSTAG [10] standard model library [11]. This model takes governor, turbine, reheater and boiler into account. The total mechanical power output is composed of 2 proportions. Alpha proportion represents high pressure turbine whereas, (1 - Alpha) represents low pressure turbine. The integration of the difference between the high

pressure and low pressure flow represents reheater. STAT represents the speed droop. Thereby, the output of the governor is given by sum of reference power and speed deviation/STAT. The speed deviation is filtered by a dead band. Gas turbine and combined cycle plant with single shaft turbine is based on the model as proposed by [12]. Wind turbine is modelled as Type 4B wind turbine (fully rated converter based wind turbine) per IEC Generic Dynamic Model of wind turbines. The active power control of type 4B wind turbine is shown in Fig. 2. The current command to the converters (i_{pcmd}) is based on the reference power input p_{WTref} . Therefore, reference power p_{WTref} needs to be changed when change in frequency is detected. Fig. 2 also shows the droop control from the wind turbine. When frequency change is detected out of the dead-band (used to filter out small frequency fluctuations), the change in the frequency is multiplied with gain K_P and added to initial p_{WTref} .

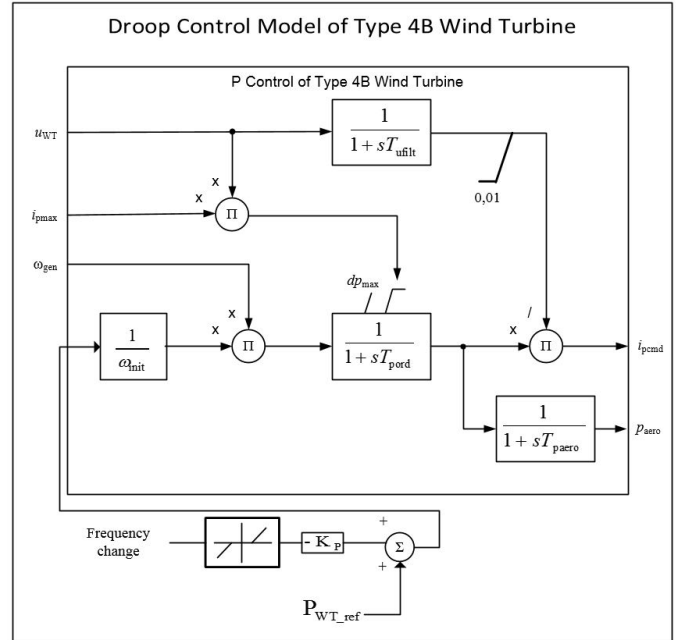


Fig. 2. P-control of Type 4B Wind Turbine [8]

III. CASE STUDIES AND RESULTS

Capacities of different types of generators are given in Table I. As can be seen from Table I, hydro and gas turbine based

TABLE I
CAPACITY OF THE GENERATORS [MW]

Steam	Wind	Hydro	Combined Cycle	Total
4160 - x	x	10	970	5140

plants are operated at their maximum capacities. Whereas, capacity of wind turbines partially replaces that of the steam

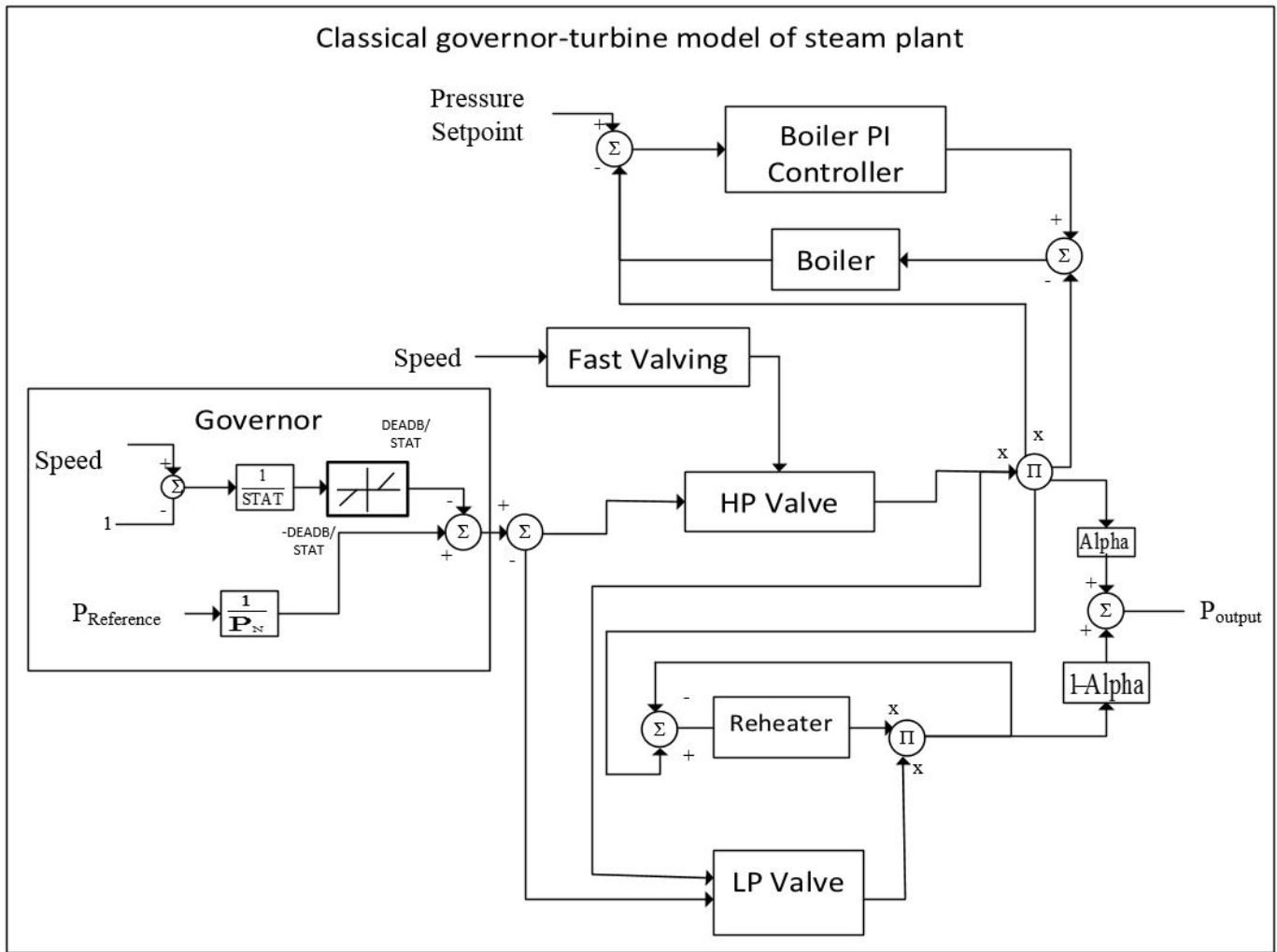


Fig. 1. Classical governor-turbine model of steam generator

turbine. Wind power penetration is defined as:

$$Wind\ Penetration[\%] = \frac{x}{Total\ Capacity} * 100\%$$

where, x = capacity of installed wind power (1)

Two case studies have been made in this paper. In the first case study, all the primary reserves are deployed on the steam turbines based generators. Whereas, in the second case study, primary reserves are supplied from the wind turbines. In both the case studies, disconnection of a 400 MW generation (no reserve has been deployed on this specific generator) is considered as reference incident in this synthetic model.

A. Case Study: Primary reserves deployed in steam turbines based generators

In this case study, all the primary reserves are supplied from steam turbines based generators. The effect of primary reserves on frequency stability for the reference incident is investigated. Change in frequency for different values of primary reserves are shown in Fig. 3 for zero penetration of wind power. It

can be observed from Fig. 3 that when primary reserve is 100 MW, the frequency is unstable. As primary reserve increases, system frequency starts stabilizing. It is important to note that even if the frequency stabilizes to frequency higher than 49 Hz after primary reserves are completely deployed, it is possible that frequency nadir can go below 49 Hz.

With increase in wind penetration replacing conventional generations, total inertia of the system decreases. The change of inertia with increase in wind penetration displacing conventional generations is shown in Fig. 4. It can be seen from Fig. 4 that system inertia decreases quite substantially with more and more displacement of conventional generations with wind power.

Further, the effect on frequency stability for increasing degree of wind penetration and different values of primary reserves is explored. As the wind penetration replaces conventional generations, system inertia erodes, thereby the frequency nadir goes lower following the reference incident. It is investigated whether the frequency nadir is contained above 49 Hz successfully as shown in Fig. 5. The horizontal plane at

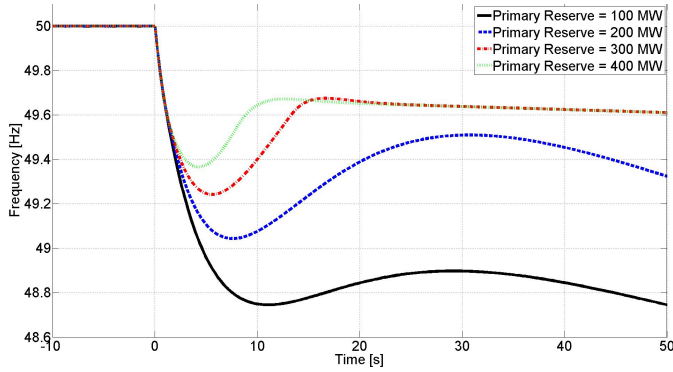


Fig. 3. Effect of primary reserves on frequency following a reference incident

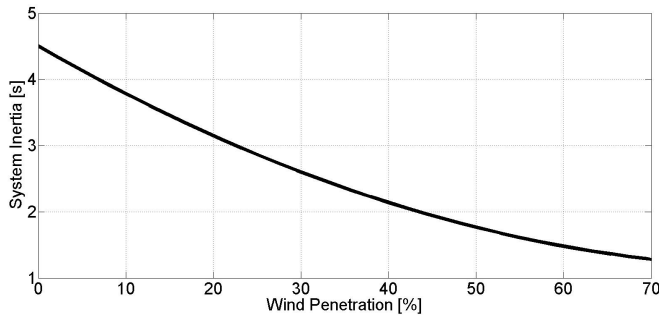


Fig. 4. Decrease of system inertia with increase in wind penetration displacing conventional generations

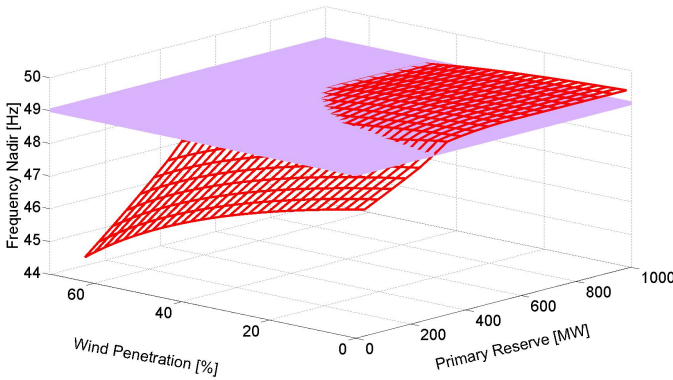


Fig. 5. Effect of increase in wind penetration (displacing conventional generators) on frequency nadir when primary reserves are supplied from steam generators

49 Hz represents the success criterion for frequency stability in Fig. 5. Therefore, when frequency nadir is above this plane, load shedding is prevented and primary control is sufficient to prevent frequency instability. It can be observed from Fig. 5 that if primary reserve volume is too low, frequency nadir can reach below 49 Hz even at zero wind penetration. With increase in wind penetration, primary reserve requirements also increase to handle the reference incident. It can be observed from Fig. 5 that beyond certain wind penetration, defined as critical wind penetration, any increase of primary reserve is not sufficient to prevent frequency nadir from going to 49 Hz.

Minimum primary reserve requirements for different degrees of wind penetration is shown in Fig. 6. It can be observed from Fig. 6, minimum primary reserve requirements increase with increase in wind penetration. Critical wind penetration is obtained to be 41.8% which has minimum primary reserve requirement of 560 MW to handle the reference incident. As can be found from Fig. 4, the system inertia at critical

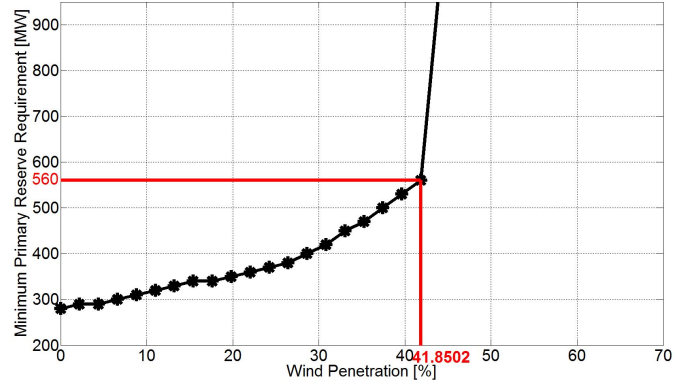


Fig. 6. Minimum primary reserve requirements from steam generators for different wind penetrations (displacing conventional generators) to prevent load shedding

wind penetration, called critical inertia is 2.136 s for this specific system. It should be emphasized that success criterion chosen for the studies here is to prevent underfrequency load shedding. Frequency nadir reaching 49 Hz does not necessarily indicates frequency instability. As can be seen from Fig. 3, primary control is often able to stabilise the frequency to a value higher than 49 Hz. However, this underlines that primary control is not fast enough to prevent underfrequency load shedding which is not desirable. This phenomenon is more prominent through Fig. 7 and Fig. 8. Effect of wind penetration on frequency at 30 s after the disturbance is observed in Fig. 7. It can be assumed that short term frequency instability can be avoided after 30s with the support from secondary control. It can be observed from Fig. 8 that wind penetration

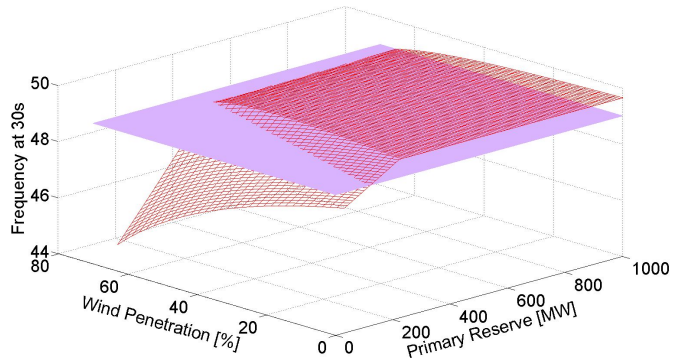


Fig. 7. Effect of increase in wind penetration (displacing conventional generators) on frequency at 30s after the disturbance

can be increased more than critical value (upto 63.2%). This

implies that from 41.8% to 63.2% wind penetration, initial frequency goes below to 49 Hz and stabilizes back to higher value. It is also interesting to note that if the minimum frequency constraint is relaxed, primary reserve requirements reduces from 560 MW to 340 MW. It is clear from the above

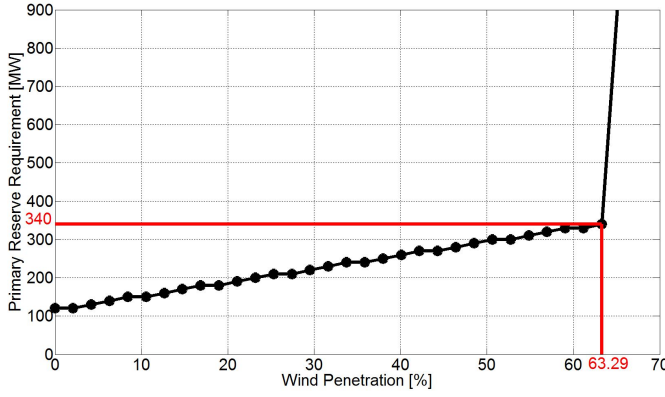


Fig. 8. Primary reserve requirements from steam generators for different wind penetrations (displacing conventional generators) so that frequency is above 49 Hz at 30 s after the disturbance

case study that in future power system with higher degree of wind penetration displacing conventional generations, not only larger primary reserve volume is required but also faster primary control is essentially required to prevent emergency load shedding.

B. Case Study: Primary reserves deployed in wind turbines

This case study takes in cognizance that power electronics based droop control from wind turbine is much faster than primary control from steam turbine. In this case study, the primary reserve is deployed in the wind turbines, which means that the wind turbines are running in downregulated condition during normal operation. It is assumed that the wind speed experienced by the wind turbines is rated wind speed and therefore, the possible power generation from the wind turbines is maximum.

Frequency support from wind turbines not only depend on the available reserves but also rate of increase in wind power output with change in frequency. This rate of change in power output depends on the K_p value of the droop control model as shown in Fig. 2. Higher the value of K_p , higher is the support from the wind turbine. For example, if K_p has a value of 10 and frequency goes down to 49 Hz (speed change = $1/50 = 0.02$ p.u.), contribution from wind turbine is increased by 0.2 p.u. (or 20%).

Effect of increase in wind penetration on frequency nadir when primary reserves are supplied from wind generators for $K_p = 10$ can be observed in Fig. 9. It can be observed that critical wind penetration is increased as compared to that of Fig. 5. It can be observed from Fig. 9 that beyond critical wind penetration it is not possible to contain frequency nadir with 49 Hz following reference incident even with increase in primary reserve. In order to increase wind penetration beyond this critical value droop control should be even faster

which can be achieved by increasing K_p . Minimum primary

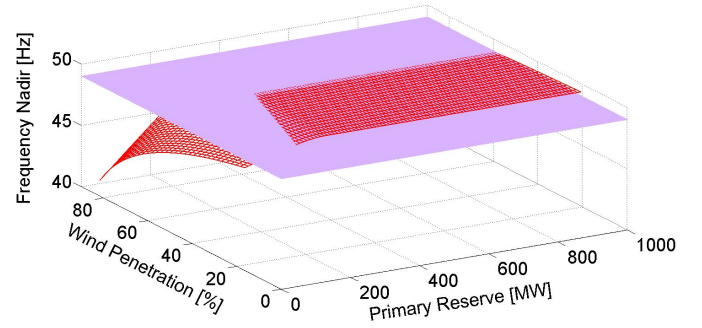


Fig. 9. Effect of increase in wind penetration (displacing conventional generators) on frequency nadir when primary reserves are supplied from wind generators for $K_p = 10$

reserve requirements and critical wind penetrations for $K_p = 10$ and $K_p = 20$ are shown in Fig. 10. It can be observed that critical wind penetration increases from 54.85% for $K_p = 10$ to 69.62% for $K_p = 20$.

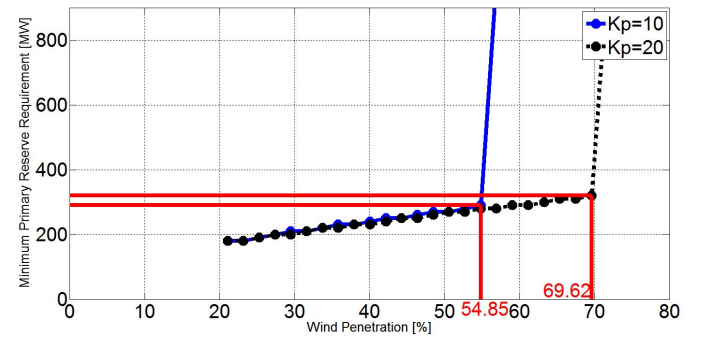


Fig. 10. Minimum primary reserve requirements from wind generators for different wind penetrations (displacing conventional generators) to prevent load shedding

It can be inferred from the above case study that in future power system, it might be imperative to supply primary reserve from wind turbines in order to have higher degree of wind penetration. Although it should be noted that higher is the primary reserve deployment from the wind turbine, it is more expensive.

IV. CONCLUSION

Low inertia of the system with high penetration of wind generation replacing conventional generation can invoke short term frequency instability. When inertia is low, the rate of change of frequency is fast and as a result system can move to emergency state even before secondary control is activated. Primary control from conventional generators may not be adequate and fast enough to contain the frequency. Faster active power support from wind turbines provides better support to stabilize the frequency than conventional primary control. Therefore, primary or droop control support from the wind generators may be essentially required when the penetration of the wind power is much higher. This paper motivates the

research requirement for analytical quantification of primary reserves for future power systems with high penetration of wind power.

REFERENCES

- [1] EWEA, "Pure Power," 2011. [Online]. Available: http://www.ewea.org/fileadmin/ewea_documents/documents/publications/reports/Pure_Power_III.pdf
- [2] P. Kundur et al., "Definition and classification of power system stability," *IEEE Transactions on Power Systems*, vol. 19, no. 3, pp. 1387–1401, Aug. 2004.
- [3] CIGRE Task Force C2.02.24, "Defense Plans Against Extreme Contingencies," Technical Brochure, April 2007.
- [4] "Technical Background and Recommendations for Defence Plans in the Continental Europe Synchronous Area," Prepared by the Sub Group 'System Protection And Dynamics' Under Regional Group Continental Europe, ENTSO-E, Oct 2010.
- [5] I. D. Margaritis, S. A. Papathanassiou, N. D. Hatziaargyriou, A. D. Hansen, and P. Sørensen, "Frequency control in autonomous power systems with high wind power penetration," *Sustainable Energy, IEEE Transactions on*, vol. 3, no. 2, pp. 189–199, 2012.
- [6] K. Das, A. D. Hansen, and P. E. Sørensen, "Aspects of Relevance of Wind Power in Power System Defense Plans," in *12th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants*, 2013, pp. 416–421.
- [7] F. Villella, S. Leclerc, I. Erlich, and S. Rapoport, "PEGASE pan-European test-beds for testing of algorithms on very large scale power systems," in *2012 3rd IEEE PES International Conference and Exhibition on Innovative Smart Grid Technologies (ISGT Europe)*. IEEE, 2012, pp. 1–9.
- [8] Standard, IEC, "IEC 61400-27-1: Wind turbines - Part 27-1: Electrical simulation models - Wind turbines," *Final Draft International Standard*, pp. 61 400–27–1, 2014.
- [9] Handbook, UCTE Operations, "P1–Policy 1: Load-Frequency Control and Performance [C]," *Version: v3. 0 rev*, vol. 15, no. 01.04, 2009.
- [10] B. Meyer and M. Stubbe, "Eurostag, a single tool for power system simulation," *Transmission & Distribution International*, 1992.
- [11] Tractebel-RTE, "Standard Models Library, EUROSTAG."
- [12] W. I. Rowen, "Simplified mathematical representations of heavy-duty gas turbines," *Journal of Engineering for Gas Turbines and Power*, vol. 105, no. 4, pp. 865–869, 1983.